Measurement of Cross Sections with Neutrons as Targets. II*

M. WIDGOFF
Brown University, Providence, Rhode Island

AND

A. M. CORMACK
Tufts University, Medford, Massachusetts

AND

A. M. KOEHLER
Harvard University, Cambridge, Massachusetts

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This report describes a measurement of the proton-neutron total cross section σ_{pn} by the Chew-Low extrapolation technique, carried out with protons of 89 MeV incident on deuterium. The purpose of the experiment was to provide an additional test of the Chew-Low method, supplementing a previous test near 160 MeV. The method is difficult to apply, but the measured values of σ_{pn} around 89 MeV again give sufficiently good agreement with σ_{np} values obtained by direct scattering methods to give confidence in the technique for the determination of the neutron-neutron cross section.

INTRODUCTION

IN 1959 Chew and Low[1] proposed a method whereby the results of scattering experiments performed with complex particles as targets could be analyzed so as to yield the cross section for scattering of the incident particle by an individual elementary component of the complex target. Under the assumptions made by Chew and Low, the resulting two-body cross sections are free of binding effects. The special interest in this proposal lies in the prospect it presents of finding cross sections with unstable particles as targets—particles of which laboratory targets cannot be constructed. For example, by the Chew-Low method, the neutron-neutron cross section can be determined by using deuterons as targets, and pion-pion interactions can be studied by treating the pion as a constituent of a proton target. The present experiment provides a test of the Chew-Low method, by using it to obtain the proton-neutron cross section from proton-deuteron scattering at 89 MeV, and then comparing the results to the directly measured neutron-proton cross section. This is an extension to a lower-energy region of an experiment done at 160 MeV.[2]

CHEW-LOW EXTRAPOLATION METHOD

Consider the interaction

$$p+d \rightarrow p+p+n \qquad (1)$$

represented by the diagram in Fig. 1. This diagram shows a single-particle intermediate state, a neutron. Chew and Low conjecture (a) that there is a pole in the S matrix for this diagram at a point related to the mass of the neutron, and (b) that the residue at this pole is given by the product of the smaller dimensional S-matrix elements which connect the two groups of particles, respectively, to the intermediate particle. The matrix element at vertex A is that for the transition $d \leftrightarrows n+p$, and this is known to be directly related to the normalization of the asymptotic wave function of the deuteron. Chew and Low assume (c) that the matrix element connecting the particles of group 2 to the intermediate particle (at vertex B) is equal to the physical matrix element for the interaction between the incoming proton and the intermediate particle to yield the particles F. At the pole mentioned above, the proton in the deuteron acts as a noninteracting spectator.

Let M_p be the mass of the proton; T_{2L}, the laboratory system kinetic energy of the recoil proton; θ_L, the laboratory angle of the recoil; and $p^2=2M_pT_{2L}$, the nonrelativistic momentum of the recoil. Also, let q_{1L} be the laboratory momentum of the incoming proton; M_d, the mass of the deuteron; M_n, the mass of the intermediate particle (the neutron); w, the total energy of particles F (which include all the outgoing particles except the recoil or spectator) in their center-of-mass system.

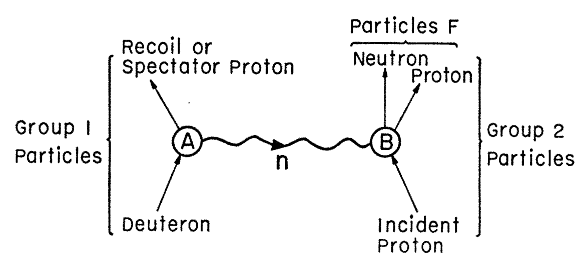

FIG. 1. Diagram of the reaction $p+d \rightarrow p+p+n$ with a neutron as the single particle state linking particles of group 1 and group 2. The vertex B represents the interaction of interest: $p+n \rightarrow p+n$.

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[1] G. F. Chew and F. E. Low, Phys. Rev. 113, 1640 (1959).

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In accordance with conjecture (a), the pole in the S matrix occurs at $P^2=-M_n^2$, where P^2 is the square of the total energy-momentum four-vector for each of the sets of particles labeled Group 1 and Group 2, respectively, in Fig. 1. It is convenient, however, to carry out the calculation in terms of the variables p^2 and w^2. Then the pole occurs at

$$p^2=p_0^2=-(M_p/M_d)[M_n^2-(M_p-M_d)^2], \qquad p_0^2=-0.2091\times10^4\ (\text{MeV}/c)^2, \tag{2}$$

a negative, nonphysical value of p^2. The residue $F(p_0^2,w^2)$ at this pole is found by extrapolating into the nonphysical region to $p^2=p_0^2$, at fixed w^2, the experimentally determined function

$$F(p^2,w^2)=2\pi\left(\frac{M_d}{M_p}\right)^2 \times\frac{q_{1L}^2(p^2-p_0^2)^2}{[\frac{1}{4}w^4-\frac{1}{2}w^2(M_n^2+M_p^2)+\frac{1}{4}(M_n^2-M_p^2)^2]^{1/2}} \times\frac{\partial^2\sigma}{\partial(p^2)\partial(w^2)}. \tag{3}$$

Then we have, through conjectures (b) and (c),

$$F(p_0^2,w^2)=\frac{4}{M_p}\frac{\alpha}{1-\alpha r_0}\sigma_{pn}(w)=\frac{1}{K}\sigma_{pn}, \tag{4}$$

where $2\alpha/(1-\alpha r_0)=C^2$, the square of the normalization of the asymptotic deuteron wave function, α is the inverse deuteron radius ($=23.18\times10^{11}$ cm^{-1}) and r_0 is the n-p triplet effective range ($=1.74\times10^{-13}$ cm).[3] The pole occurs at $p^2=p_0^2=-\alpha^2$.

Now,

$$w^2=(\omega_{1L}+M_d-M_p-T_{2L})^2 -(q_{1L}^2-2q_{1L}p_{2L}\cos\theta_L+p_{2L}^2), \tag{5}$$

with ω_{1L} and q_{1L} as the total laboratory energy and momentum, respectively, of the incoming particle, p_{2L} the momentum of the recoil proton, and the other symbols as defined above. Thus, by measuring the energy and direction of a recoil proton, we can obtain the corresponding $p^2=2M_pT_{2L}$ and w^2. From the two-dimensional distribution in p^2 and w^2 of the recoil particles, we determine $\partial^2\sigma/\partial(p^2)\partial(w^2)$, and calculate $F(p^2,w^2)$.

Since the function F must be extrapolated to a negative value of p^2, it is clearly important to measure $\partial^2\sigma/\partial(p^2)\partial(w^2)$ at the lowest possible values of p^2. In the deuteron case, the allowable phase space for the spectator particle includes $p^2=0$, so that only experimental problems affect the measurement of low values of p^2.

[3] Richard Wilson, *The Nucleon-Nucleon Interaction* (Interscience Publishers, Inc., New York, 1963).

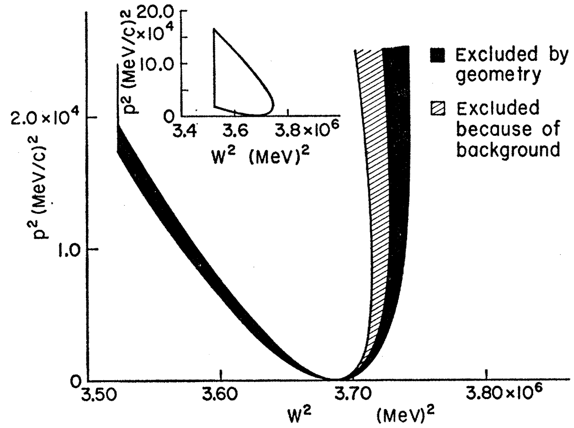

FIG. 2. Phase space available to a proton from the interaction $p+d\rightarrow p+p+n$, for incoming protons of 90 MeV. The variable p^2 is the square of the nonrelativistic momentum of one of the protons (the spectator), while w^2 is the total energy in the center-of-mass system of the other proton and the neutron. The total available phase space is shown in the inset, while the portion of interest, where p^2 is small, is shown enlarged. The geometry of this experiment was such that events in the blackened region could not be observed. The shaded region contained many background tracks, and hence was avoided. The background in the clear region was negligible.

A number of experiments have been performed which make use of the Chew-Low extrapolation method.[4] However, as pointed out by Chew and Low,[1] by Blankenbecler *et al.*,[5] and by Aitchison,[6] there are other singularities in the scattering amplitude which may interfere with the extrapolation to p_0^2. Several tests of the method have been carried out, with different experimental methods and at various energies: measurements of proton-neutron differential cross sections by the extrapolation method have been made by Kuckes, Wilson, and Cooper[7] at 145 MeV and by Carlson[8] at 40 MeV, and in both cases the results agreed with the directly measured np cross sections. On the other hand, Griffiths and Knight,[9] studying the proton-proton differential and integrated cross sections at 50 MeV, found that the extrapolation method did not give values in agreement with the directly measured cross sections.

This paper presents a report on a test of the Chew-Low method carried out by using the technique to determine the proton-neutron total cross section, and comparing the results thus obtained with values of the

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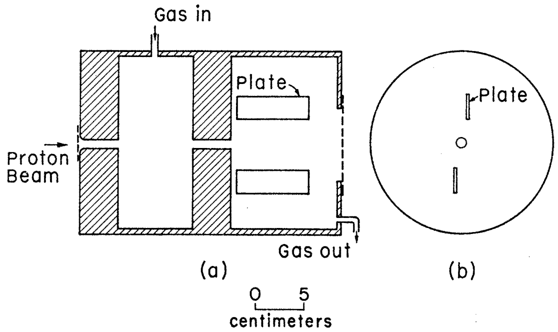

FIG. 3. (a) Schematic diagram of target-camera chamber, showing the final collimating and antiscattering slits, and the plate positions. (b) End view, drawn looking into the beam.

neutron-proton cross section previously determined from the scattering of neutrons incident on hydrogen targets. The experiment discussed here was carried out with protons of 89-MeV energy incident on a deuterium target. A similar experiment, done by our group with incident protons of 160 MeV energy, has already been reported,[2] and will be referred to hereafter as I. The results of that experiment appeared to confirm the validity of the Chew-Low extrapolation technique. This earlier paper should be consulted for details of the procedures of exposure and of data analysis, which will be only briefly presented here.

EXPERIMENTAL PROCEDURE

The experiment was performed at the Harvard synchrocyclotron. The 160-MeV proton beam emerging from the cyclotron was reduced in energy to 89 ± 1 MeV by the use of suitable carbon absorbers. The beam energy was verified by range measurements. Low-energy contamination in the degraded beam was eliminated by an analyzing magnet.

The phase space available to protons from interaction (1), with incident protons of 90 MeV, is shown in Fig. 2. This figure shows that $p^2=0$ at a single value of w^2. This value, $w^2=w_0^2$, is

$$w^2=w_0^2=W^2+M_p^2-(M_p/M_d)(W^2+M_d^2-M_n^2), \quad (6)$$

where $W=(2M_d\omega_{1L}+M_d^2+M_p^2)^{1/2}$ is the total energy in the over-all center-of-mass system of interaction (1). The energy w_0 is also the final center-of-mass energy which corresponds (neglecting the binding shift) to the collision of the incident proton with a neutron at rest in the laboratory. It is, therefore, the best value of w^2 at which to make the extrapolation.

In order to observe low-energy protons from interaction (1), a target of gaseous deuterium was used, with nuclear-emulsion plates as detectors placed around the target volume. The entire camera-target chamber (Fig. 3) was filled with deuterium, and no wall intervened between target and detector. With deuterium at a pressure of approximately one atmosphere and the emulsion array as shown in Fig. 3, it was possible to detect protons produced in the target volume with $25°<\theta_L<160°$ and with energies as low as 1 MeV. A large number of the recoil protons stopped in the dense material of the nuclear emulsion, so that their ranges and, hence, their energies, as well as their directions, could be determined with precision. Particles coming from the target volume had sufficiently small dip angles in the emulsion, and, thus, sufficiently long potential ranges to ensure that almost all particles of energies smaller than or equal to 20 MeV [$p^2=3.7\times10^4$ $(\mathrm{MeV}/c)^2$] came to rest in the emulsion. The only exceptions were particles which interacted in the emulsion, or whose trajectories were so flat relative to the emulsion plane that multiple scattering caused them to re-emerge from the emulsion surface. The radius of the target volume was set by the cross section of the beam itself. In order to have a well-defined target volume, it was necessary that the main part of the beam be contained within a radius small compared with the target-detector distance, and that the beam intensity drop off rapidly at the radial boundary. This latter requirement was essential in order to reduce the background of tracks from sources other than the target volume, as the target was of such small size and low density compared with the plates and the plate holder. Because of scattering in the degraders, the 89-MeV beam had a larger radius than the 160-MeV beam. By focusing and collimation, a reasonable signal-to-noise ratio was obtained, although it was not as good as the ratio at 160 MeV. The proton flux during the exposure was measured by means of a nitrogen-filled ion chamber which was calibrated by comparison with a Faraday cup.

DATA ANALYSIS

The nuclear emulsions were scanned for tracks of particles appearing to come from the target volume. All tracks were required to satisfy certain geometric criteria to ensure that the particles had come from the target volume. Many tracks were eliminated by the scanner on the basis of gross direction observations—such tracks were counted for background analysis but not measured. For all tracks which passed the first direction criteria, measurements were made of length, dip angle, and projected angle (in the plane of the emulsion). Such tracks were then accepted if the calculated line of flight of the particle extended through the target volume. Most particles in the phase space region of interest came to rest in the emulsion: for these the range traversed in emulsion and deuterium gave a precise determination of T_{2L}. The direction θ_L was also determined with good resolution. From these measurements $p^2=2M_pT_{2L}$ and w^2, given by Eq. (5), were determined for each recoil proton. A two-dimensional distribution in p^2 and w^2 then gave $\partial^2\sigma/\partial(p^2)\partial(w^2)$ and, hence, the function $F(p^2,w^2)$ shown in Eq. (3). Corrections were made for particles which interacted or scat-

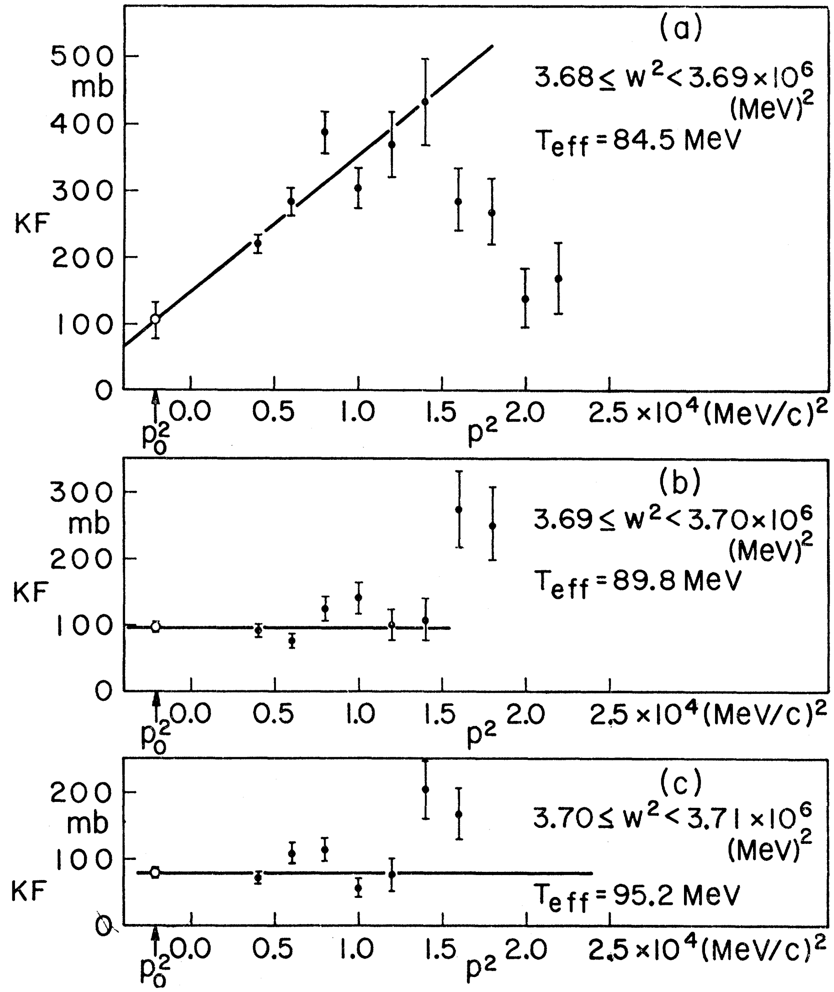

FIG. 4. $KF(p^2,w^2)$ versus p^2 for three intervals in w^2. K is defined by Eq. 4. The line drawn in each case represents the lowest order polynomial in p^2 which fits the data satisfactorily. The extrapolations to $p^2=p_0^2$, where $KF(p_0^2)=\sigma_{pn}$, are given, with the statistical errors. The solid circles are the measured points, and the open circles are the extrapolated points.

tered out of the emulsion layer before coming to rest; these corrections amounted to a few percent over most of the region of interest. The method of making the corrections was described in I.

A further word should be said about background. As mentioned above, the background of particles coming from regions outside the target volume was easily eliminated by discarding tracks whose initial directions in the plate did not project back through the target volume. This procedure could not eliminate those particles which originated in material beyond the target, and which then passed through the target on their way to the emulsion. That there was a negligible number of such particles is indicated by the fact that few acceptable tracks were found in an exposure made with the target chamber evacuated. Where such tracks did occur in the vacuum exposure, they were confined almost entirely to the portion of phase space which is shown shaded in Fig. 2. This region contains the smaller forward scattering angles, $\theta_L<\sim 45°$, and is also the region where the corrections for particles leaving the emulsion are largest. For these reasons, the data from this region were not used in the extrapolation.

Another source of background which could not be eliminated by geometrical considerations was contamination in the deuterium target. The deuterium was supplied with a purity of 99.7%. The major source of contamination was outgassing from the emulsion material itself. This outgassing rate was reduced by pumping on the emulsion for two hours before filling the chamber with deuterium for an exposure. The rate of pressure rise in the target chamber when isolated from the pumping system was thus reduced to 1×10^{-2} (mm Hg)/min. Contamination from outgassing was then limited to 1% or less by maintaining a steady flow of fresh deuterium through the target chamber, at the requisite rate.

Scanning efficiencies, solid angle considerations, and other factors affecting the determination of $\partial^2\sigma/\partial(p^2)\partial(w^2)$ were discussed in detail in I; the same methods and procedures have been used in this experiment.

TABLE I. Results of least-squares fitting and extrapolation.

Energy interval $(\text{MeV})^2$	Number of tracks	Form of fitted function	Number of constraints	χ^2	$P(\chi^2)$	$KF(p_0^2,w^2) = \sigma_{pn}(w^2)$ (mb)
$3.68\times10^6 \leq w^2 < 3.69\times10^6$	370	$KF=a$	5	5.52	35%	269.5 ± 16.8
($T_{\text{eff}}=84.5$ MeV)	370	$KF=a+bp^2$	4	0.77	94%	105.3 ± 27.1
$3.69\times10^6 \leq w^2 < 3.70\times10^6$	120	$KF=a$	5	0.97	96%	$96.3\pm\ 5.2$
($T_{\text{eff}}=89.8$ MeV)	120	$KF=a+bp^2$	4	0.60	96%	67.5 ± 14.2
$3.70\times10^6 \leq w^2 < 3.71\times10^6$	90	$KF=a$	4	0.97	91%	$79.2\pm\ 5.8$
($T_{\text{eff}}=95.2$ MeV)	90	$KF=a+bp^2$	3	0.97	81%	80.9 ± 18.7

RESULTS AND DISCUSSION

The variable w^2 is the square of the total energy in their c.m. system of the two particles going out at vertex B in Fig. 1. Values of the effective energy T_{eff} of the incoming proton in the two-body system at vertex B can be calculated, corresponding to various values of w^2. When the extrapolation to p_0^2 is carried out at fixed w^2 the cross section obtained through Eqs. (3) and (4) is $\sigma(w^2)$, or $\sigma(T_{\text{eff}})$, for the two-body interaction.

The function F cannot be experimentally determined at a point (p^2,w^2); it is necessary to group together particles in finite intervals $(\Delta p^2,\Delta w^2)$ and to find an average $\partial^2\sigma/\partial(p^2)\partial(w^2)$ in each such interval. The intervals should be taken as small as is feasible in order that the averaging in each interval be done over regions of small variation. However the intervals must be large enough to include a sufficient number of tracks to give each value of $F(p^2,w^2)$ a reasonable statistical weight. In this 89-MeV experiment, Δw^2 has been made much smaller than it was in the 160-MeV experiment, because the cross section is varying much more strongly with energy in the 89-MeV region. The experimentally determined points $KF(p^2,w^2)$ for three different intervals of w^2 are plotted in Fig. 4. The results shown in Fig. 4(a) correspond to the interval which includes w_0, the energy at which the condition of a two-body interaction is most closely approached. The form of these results is very similar to the form of the results found at the corresponding value of w in our 160-MeV experiment, namely, an initial rise followed by a drop at high values of p^2. In Figs. 4(b) and 4(c) $w\neq w_0$, and, again, the form of the results is similar to the corresponding form at 160 MeV, namely, a flat region followed by a rise at large p^2.

The upper limit of p^2 used in the extrapolations was chosen in each case to avoid the very marked changes in slope of KF vs p^2 mentioned above. Such changes might be due in part to the effect of final state interactions[6] which are likely to be negligible at low p^2. The use of points above the chosen upper limits was undesirable, also, because of the increasing size of the correction which had to be made for the particles leaving the emulsion. The lower limit of p^2 was set at $p^2=0.3\times10^4$ $(\text{MeV}/c)^2$, corresponding to a kinetic energy of 1.6 MeV, because of inefficiency for counting the short tracks of particles of lower energy, and because of the greater difficulty of making precise measurements on them.

The results of least-square fits and of the extrapolations are given in Table I. Where the data can be fitted by a zero-order polynomial in p^2, or, in other words, where $KF(p^2,w^2)$ is consistent with being constant as p^2 is varied, a rather well-determined value of $\sigma(w^2)$ is obtained with limited data. This is the case for the intervals $3.69\times10^6 \leqslant w^2 < 3.70\times10^6$ MeV^2 and $3.70\times10^6 \leqslant w^2 < 3.71\times10^6$ MeV^2, where the statistical errors in the cross sections are about 5% and 7%, respectively. For the interval $3.68\times10^6 \leqslant w^2 < 3.69\times10^6$ MeV^2, a first-order polynomial in p^2 is required to fit the data, and, here, the statistical error in $\sigma(w^2)$ is 26%. No lower values of w^2 were used, as it was found that higher-order polynomials were required for fitting these, and the errors made the results meaningless. For example, in the interval $3.67\times10^6 \leqslant w^2 < 3.68\times10^6$ MeV^2, where a second-order polynomial in p^2 was needed to fit the data, the error in the cross section was more than 100%: $\sigma(w^2=3.675\times10^6)=94\pm106$ mb.

Figure 4 and Table I illustrate some of the difficulties encountered in the experimental application of the extrapolation method. A major problem lies in amassing sufficient data. The plotted points have rather large statistical errors, since the number of events accumulated in each box of the two-dimensional p^2-w^2 array is a small percentage of the total measured. A more fundamental difficulty is the choice of the form of the extrapolation curve. The results of this experiment, as well as those in the cited references, demonstrate that quite different cross sections can result from the choice of different polynomials. The practice has been to choose the lowest-order polynomial that fits the data reasonably well, since this gives the most precisely determined value of the cross section. The data sometimes limit the choice, as they appear to do for Fig. 4(a). However, in Fig. 4(b), for example, the χ^2 values for the zero-order and first-order polynomials are not very different, while the cross sections do differ appreciably. There is, thus, a certain arbitrariness in the application of the method.

The errors discussed above and shown in Fig. 4 and in Table I are the standard deviations arising from

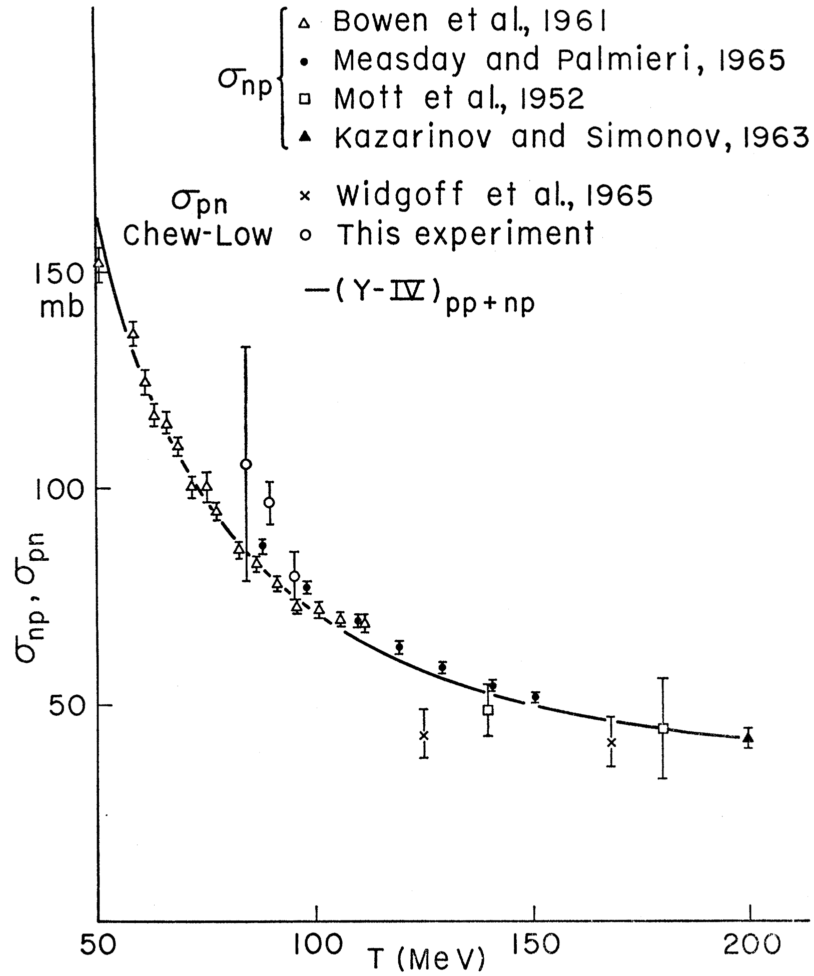

FIG. 5. Comparison of σ_{pn} measured in this experiment using the Chew-Low method, with measurements of σ_{np} in the same energy region. T is the nominal kinetic energy of the incoming particle. The curve is based on the Yale phase-shift analysis.

counting statistics only. There are uncertainties in other factors that enter into any cross section measurement, such as the beam intensity, the target density, the efficiency of detection, and the solid angle factors. These together contribute a further uncertainty of about 12%. The contributions to the uncertainty in F of errors in measurement of q_{1L}^2, p^2, and w^2 are at most about 2%, much smaller than the statistical uncertainty in $\partial^2\sigma/\partial(p^2)\partial(w^2)$. All these sources of error contribute to the uncertainties of a direct cross section measurement as strongly as they do to a Chew-Low determination. It is the statistical errors that show the difficulty inherent in the extrapolation method. The required distribution of the events in a two-dimensional array means that even with a large total number of tracks, the individual values of $\partial^2\sigma/\partial(p^2)\partial(w^2)$ and, hence, of $F(p^2,w^2)$ have large statistical uncertainties.

The σ_{pn} cross sections determined by the extrapolation of the lowest order polynomials are compared in Fig. 5 with np cross sections. Experimental values of σ_{np} measured by Bowen *et al*,[10] Mott *et al*,[11] Kazarinov and Simonov,[12] and Measday and Palmieri[13] are plotted. Of these, the last are the most recent, and, we believe, the most reliable. The curve shows σ_{np} as a function of the energy of the incoming neutron, as calculated from the Yale phase-shift analysis[14] of nucleon-nucleon scattering data. When the errors are considered, the agreement between the values of σ_{pn} obtained by the extrapolation and σ_{np} obtained by direct measurement is not bad.

CONCLUSION

The Chew-Low extrapolation technique has been used to measure σ_{pn} in two energy regions, around 90 MeV in the present experiment and around 160 MeV in

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I. The results obtained using the extrapolation method are in reasonable agreement with directly measured values of σ_{np} shown in Fig. 5, when the experimental uncertainties are taken into account. The forms of the extrapolation functions are the same for both energy regions.

An inescapable conclusion to be drawn is that the method is hard to apply because of the difficulty of accumulating sufficient data to establish each value of $\partial^2\sigma/\partial(p^2)\partial(w^2)$ to good statistical accuracy and because of the uncertainty about the form that the extrapolation function should take, a point on which the theory has nothing to say. Nevertheless, we believe that we have found empirically a method for making the extrapolation correctly for the pn system, and that the same procedures can be used to measure σ_{nn} by the Chew-Low method.

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Inelastic Nuclear Interactions of High-Energy Electrons and Muons in Emulsion*

Richard L. Thompson† and J. J. Lord
University of Washington, Seattle, Washington 98105

AND

James A. Kirk
Idaho State University, Pocatello, Idaho 93201

AND

Martin E. Nelson‡
University of Puget Sound, Tacoma, Washington 98416

AND

Robert J. Piserchio
San Diego State College, San Diego, California 92115

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An experiment has been carried out to examine the inelastic nuclear interaction properties of high-energy electrons and muons in emulsion. A study was made of interactions produced by 10.5-GeV muons and 10.0- and 16.0-GeV electrons. Total and differential cross sections have been measured and compared with calculations carried out with the formulation of Hand and Wilson for inelastic lepton scattering. On the basis of the calculations, the ratio of electron to muon total cross sections was found to be 3.5:1, whereas experimentally the ratio was measured to be 2.18±0.40 for the 10-GeV leptons. To explain the total cross section for electrons, an average scalar-photon contribution equal to 12% of the transverse-photon cross section is needed, which is consistent with other experiments. The muon cross section was found to be significantly larger than expected, and it cannot be explained by a similar scalar-photon contribution. The energy dependence of the total cross sections is in agreement with theory, as are the angular distributions of the scattered leptons.

I. INTRODUCTION

THE inelastic nuclear scattering of electrons and muons provides direct information on the applicability of quantum electrodynamics. It also serves to examine any possible differences in the nature of the interactions for the electron and muon. In order to investigate these two questions, an experiment has been carried out with photographic emulsions exposed to 10.0- and 16.0-GeV electrons at the Stanford Linear Accelerator and 10.5-GeV muons at the Brookhaven Alternating Gradient Synchrotron. In addition, previous muon exposures at 2.5 and 5.0 GeV have been reexamined to supply a comprehensive analysis of the inelastic lepton interaction over a wide range of energies.

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† Present address: Humboldt State College, Arcata, Calif.

‡ NSF Science Faculty Fellow.